

# Upgrading of induction motors with energy efficiency enhancement at the electrical repair shops and sites of the running industrial companies

R G Mugalimov<sup>1,3</sup>, A R Mugalimova<sup>2</sup> and R A Zakirova<sup>1</sup>

<sup>1</sup> Federal State-Funded Educational Institution of Higher Professional Education 'Magnitogorsk State Technical University named after G I Nosov', Magnitogorsk, 455000, Russia

<sup>2</sup> Scientific Research and Design Bureau 'Energoberezhniye' LLC, Magnitogorsk, 455000, Russia

E-mail: <sup>3</sup> energoberegenie@rambler.ru

**Abstract.** It is demonstrated that the main disadvantage of induction motors is a relatively low power factor. In order to enhance energy efficiency of the electric drives, it is proposed to use an innovative technology of their upgrading in the course of overhauls. A distinctive feature of the proposed overhaul is the recalculation of the stator winding considering the real state of the stator steel and uses the phenomenon of current ferro-resonance in the machine's electromagnetic system. This makes it possible to create an induction motor with the desired power factor, even equal to one. Upgrading allows increasing the efficiency factor and reducing the active power losses by 3–7% in the electric drive system and in the power supply system. Additional expenses for upgrading costs amount to 23–30% of the conventional overhaul costs. However, these additional expenses can be justified within 0.25–0.8 years due to energy savings. The results of this R&D project can be recommended for review to the power departments of the running industrial companies, electrical repair shops and energy saving centers.

## 1. Introduction

Up to 80% of electric drives of working machines and mechanisms at the Russian industrial facilities are based on traditional induction motors (TIM). This is due to their high reliability and low maintenance costs. However, the energy efficiency factor of TIM, as measured by electrical efficiency and power factor, is relatively low. Depending on the power and rotor speed, the rated efficiency and  $\cos\varphi$  are within the following range: efficiency = 65–93%,  $\cos\varphi$  = 0.7–0.9 [1]. The smaller numbers refer to the low-power motors. Their energy efficiency, equal to the product of electrical efficiency and power factor, is within the range of 46–84%. This means that between 16 and 54% of the consumed electrical energy is dissipated in the environment. Between 7 and 35% of the energy is lost directly in the TIM, and between 9 and 19% – in the power supply systems and drive circuits.

Low energy efficiency is caused by the fact that the traditional induction motors consume not only active power, which is converted into mechanical and thermal energy, but also reactive power (idle current), which is not converted into other types of energy. Reactive idle current, running in the power circuits of the drive and power supply system, causes active power losses. The lower is  $\cos\varphi$ , the higher is the loss of active power, and the less efficient is the electrical system. Theoretical and



experimental studies, as well as practical experience have proved that up to 4.5–6.0% of electrical energy is lost in the electrical facilities because of the relatively low  $\cos\phi$ . Given the average annual electricity production of 1.1 trillion kWh, the share of induction electric drive in the industry of 85 % (0.85 relative units), the average motor load factor of 75% (0.75 relative units), with consideration of losses from reactive idle current, the loss of electric energy of the Russian companies is estimated at the level of 31.5 billion kWh. Therefore, the problem of enhancement the energy efficiency of electrical facilities is of great importance.

The international standard IEC 60034 defines the energy efficiency of induction motors with four levels of energy efficiency classes: IE1 – standard efficiency; IE2 –high efficiency; IE3 –premium efficiency; IE4 –super premium efficiency. In the countries of the European Union, the use of electric motors with certain levels of energy efficiency is prohibited in accordance with the Regulation of the commission (EU) 2019/1781 document [2]. European manufacturers of induction motors upgrade their energy efficiency class by increasing the amount of active materials – electrotechnical steel, winding copper, aluminum – by an average of 20–25%, which results in efficiency gains of 1.5–3.5 %. At the same time, the cost of an energy efficient electric machine increases significantly. In the Russian Federation, the majority of general industrial induction motors with voltage of up to 1000 V and power of up to 100 kW, manufactured prior to 2010, are of standard energy efficiency class (IE1). Experience has shown that the energy efficiency of induction motors is even lower after a conventional overhaul. Laws № 197-FZ of the Russian Federation ‘On energy saving and improving energy efficiency’ dated 11.07.2011, № 200-FZ dated 18.07.2011 and № 242-FZ of 2017 prohibit the manufacture and use of induction motors of standard efficiency class [3].

It is proved that the most optimal way to reduce losses of active power in electrical engineering facilities with voltage of up to 1000V is to fully compensate the reactive power of each electrical consumer [4]. Nowadays, this is realized by parallel connection of capacitive reactive power compensators (RPC) to electrical consumers. This method is based on the current resonance phenomenon well-known in the electrical engineering, whereby the reactive induction current is compensated by the reactive capacitive current. However, the practice shows that due to significant capital costs for RPCs, the industrial companies use them for voltages of 10kV and higher, despite the fact that a significant share of electric energy is lost in networks with voltages of up to 1000V.

TIM life cycle does not exceed 25 years. During this period, the motor is overhauled from 3 to 7 times due to the destruction of the stator winding. As a rule, the overhaul involves replacing the damaged stator winding according to the original winding data. A major overhaul may involve a motor upgrade with modifications to the rated voltage and rotor speed. After each overhaul or upgrade of the TIM at the electrical repair shop of the company, its energy efficiency is usually reduced by 0.5–1.0 % [5]. Given the above, there is a problem of improving the technology of manufacturing new energy efficient induction motors and overhaul of the existing ones along with upgrading their energy efficiency class.

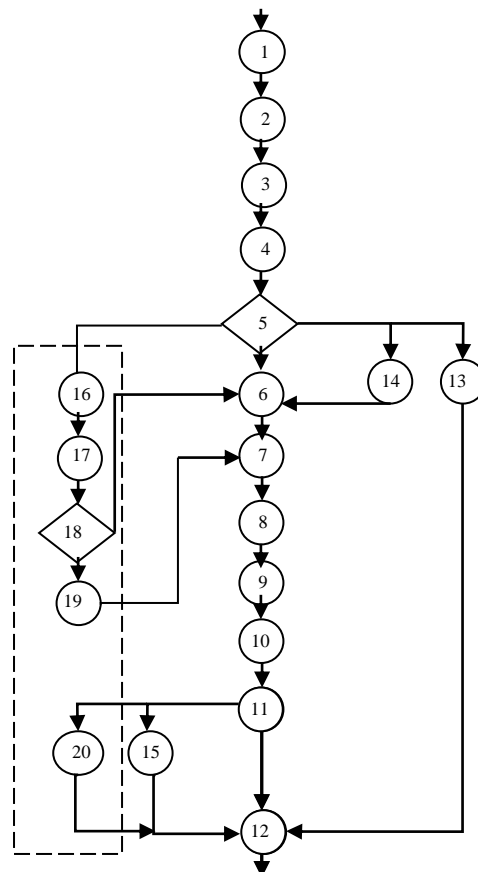
## 2. Modernization of induction motors

In contrast to technologies [6, 7] this study proposes an innovative technological scheme of overhaul of induction motors, which allows improving the energy efficiency class by upgrading the electromagnetic circuit of the stator [5]. The essence of upgrading is the improvement of the electromagnetic circuit of the stator, in accordance with invention [8]. Here the upgraded motor is called a Power-efficient Induction Motor (PEIM) with individual compensation of reactive power.

Figure 1 shows the technological diagram of overhauling and modernization of TIM in PEIM. Operations 1–15 refer to the conventional overhauling procedure of the motor. Operations 16–20, marked by a dashed line, refer to innovative technological operations. Figure 1 shows the following: 1 – disassembly of the induction motor; 2 – burnout or fluxing of the stator winding by chemical solution; 3 – removal of the stator winding; 4 – visual and instrumental assessment of the state of the electrotechnical steel of the stator; 5 – making a decision on either an overhaul according to the company's repair procedure and the TIM's diagram, or conversion of the TIM into the PEIM, or

retirement (disposal) of the induction motor; 6 – manufacturing and inserting of the stator windings according to the TIM's factory diagrams; 7 – testing of untreated stator winding; 8 – treatment of the stator winding; 9 – drying of the stator winding; 10 – assembly of the IM; 11 – testing of the IM on the inspection and testing stand; 12 – delivery of the IM to the Customer; 13 – recommendations to the Customer regarding recycling (disposal) of the IM; 14 – decrease in rated capacity  $R_{2n}$  of the TIM; 15 – experimental calibration of the motor ratings and mechanical data on the loading unit; 16 – computer recalculation of TIM winding parameters into PEIM winding parameters; 17 – computer simulation of the rating and mechanical data of PEIM; 18 – making a decision on rewinding the TIM into the PEIM or rewinding according to the factory winding data and diagrams of the TIM; 19 – rewinding the TIM into the PEIM according to the technology and manufacture diagram of the PEIM; 20 – express calibration of the motor rating and mechanical data according to the oscillograph charts of starting, reversing and braking of the IM without any load by means of a specialized hardware-software facility.

To evaluate the economic feasibility of TIM conversion into PEIM, a method and computer program has been developed [5,9].



**Figure 1.** Process stages of repair of the traditional induction motor and conversion of the traditional induction motor into the power-efficient induction motor.

Computer recalculation of TIM winding parameters to the parameters of PEIM is carried out on the basis of the experimental study of the stator steel. The essence of the approach is described below. The ferromagnetic core of the stator is tested by induction method using a motor with a rotor removed (removed from the stator bore). For magnetization of the stator core, its back is covered by an experimental magnetizing coil with a small number of windings  $W_1 = 3 \div 5$  insulated by a flexible

wire. A reference voltage is applied to the magnetizing coil  $U_{1Ref}$ , determined from the following formula:

$$U_{1Ref} = \frac{U_{1R} W_1}{W_{1EW}}, \quad (1)$$

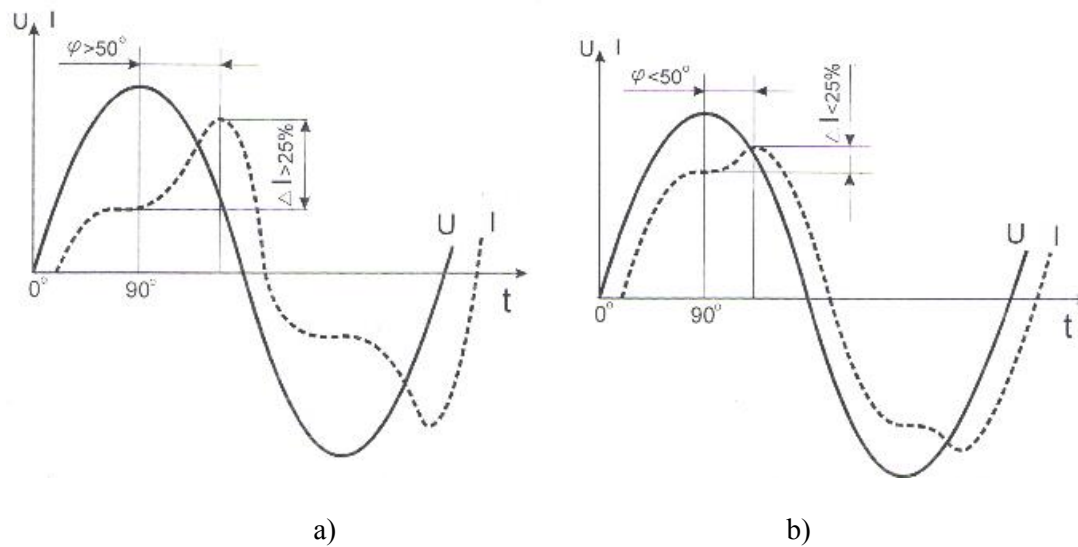
where:  $U_{1R}$  – rated phase voltage of the motor, W;  $W_{1EW}$  – number of efficient stator phase windings.

Reference magnetisation current value,  $I_{RefMm}$ , is determined from the formula:

$$I_{RefMm} = I_{Mm} \cdot W_{1EW} / W_1, \quad (2)$$

where:  $I_{Mm}$  – rated magnetizing current (no load current) of the induction motor.

With given values of  $U_{1Ref}$  and  $I_{RefMm}$  the active power losses in stator steel,  $P_{s1Ref}$  are measured with a wattmeter, and oscillograph charts of electrical values shown in Figure 2 are recorded.



**Figure 2.** Oscillograph charts of the magnetizing current and voltage:

a) for a fully operational stator core in good order; b) for a knowingly inoperable stator core.

The resulting oscillograph charts of the voltage and magnetizing current are analyzed based on the described method, and the phase shift  $\varphi_{Ref}$ , is determined by the peaks of the voltage and current curves.

$$\varphi_{Ref} = \varphi_{u\max} - \varphi_{i1\max}. \quad (3)$$

The current value is calculated at  $\varphi_u = 90^\circ$  and the difference is determined:

$$\Delta i = i_{\max} - i_{\varphi_u=90^\circ}. \quad (4)$$

For the fully operational stator core (Figure 2, a) the permissible minimum shift values of the voltage and current initial phases and  $\Delta i$  should meet the following conditions:

$$\varphi_{Ref} = \varphi_{Ref\min} > 50^\circ; \Delta i_{\min} \geq 0,25 i_{\max}; \quad (5)$$

– for a knowingly inoperable stator core, with high losses of active power (Figure 2, b) the following conditions should be met:

$$\varphi_{Ref} = \varphi_{Ref\min} < 50^\circ; \Delta i_{\min} < 0,25 i_{\max}; \quad (6)$$

– for the cores with an aluminum frame and without a frame the following conditions should be met:

$$\varphi_{Ref} = \varphi_{Refmin} > 60^\circ; \Delta i_{min} > 0,25i_{max}. \quad (7)$$

The specific losses in steel are determined by the following ratio:

$$p_{s1} = P_{s1ref}/G_{s1}, \quad (8)$$

where  $G_{s1}$  – the mass of the stator steel, in kg, determined in accordance with the known formulae.

When assessing the condition of a stator core without a frame or with an aluminum frame, the specific losses in steel,  $p_{s1}$ , should not exceed the following values:

$$p_{s1} \leq 4,5 \div 5,0 \text{ W/kg};$$

and the specific losses with provision for a steel or iron frame:

$$p_{s1} \leq (1,07 \div 1,1) * 5 \text{ W/kg}.$$

The proposed technology for the modernization of induction motors allows to increase the energy efficiency of electrical complexes by 3–7% [5, 11]. The cost of major repairs with modernization by the proposed technology, for example, an asynchronous motor of a flotation machine with a capacity of 30 kW, voltage of 380 V, magnetic field rotation speed of 750 rpm, is 36865 rub. The traditional repair of the same engine is 27397 rubles. Additional costs equal to their difference, 9468 rub were generated. The energy savings recorded during the year amounted to 10300 kWh. When the price of electric energy is 3.0 rub/kW \* hour, the cost of energy saved is 30900 rubles. Other things being equal, the payback period for additional costs does not exceed 0.3 years. The practice of modernizing induction motors according to the proposed technology for the period 2010–2019 shows that each kilowatt of installed power saves up to 350–750 kWh per year, depending on the operating conditions and loads of the electric drives.

### 3. Conclusion

1. Asynchronous motors with individual compensation of reactive power, using ferro-resonance currents in an electromagnetic system, and  $\cos\varphi = 1.0$ , they increase the energy efficiency of electrical complexes.

2. The conversion of traditional asynchronous motors to energy-efficient asynchronous motors in electric repair shops can increase the energy efficiency of industrial enterprises using asynchronous motors by 3–7%. The additional costs of modernization with an increase in the engine's energy efficiency class are justified within 0.25–0.8 years due to energy savings.

3. The results of a research project can be recommended to specialists of electric repair enterprises and energy conservation centers

### References

- [1] Kravchik A E, Shlaf M M, Afonin V I and Sobolenskaya E A 1982 *Induction motors of 4A Series: Reference Book* (Moscow: Energoizdat) p 504
- [2] Commission Regulation (EU) 2019/1781 of 1 October 2019 laying down ecodesign requirements for electric motors and variable speed drives pursuant to Directive 2009/125/EC of the European Parliament and of the Council, amending Regulation (EC) No 641/2009 with regard to ecodesign requirements for glandless standalone circulators and glandless circulators integrated in products and repealing Commission Regulation (EC) No 640/2009. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1781&from=EN> (accessed on 1 June 2020)
- [3] On energy saving and improving energy efficiency and amending certain legislative acts of the Russian Federation 2012 (Moscow: LLC 'Reed Group') p 80 (Latest legislation)
- [4] Vagin G Ya, Yurtaev S N 2008 On the necessity to adjust the method of reactive power compensation in electrical networks with voltage up to 1000V *Promyshlennaya Energetika* no 5 pp 31–40

- [5] Mugalimov R G 2011 *Induction motors with individual compensation of reactive power and electric drives [Monograph]* (Magnitogorsk: Magnitogorsk State Technical University) p 250
- [6] Mohamed K, Mahmoud E M and Abdelowahed H 2017 Evaluation of energy savings by using high efficiency motors in a thermal power station *International Journal of Green Energy* vol **14** issue **10**
- [7] EMT. 2016. EASA. The effect of repair rewinding on motor efficiency, rewind study and good practice guide to maintain motor efficiency. In website of IECEx SYSTEM. Available online: [www.iecex.com](http://www.iecex.com) (accessed on 22 March 2016)
- [8] Mugalimov R G, Savitskiy A L and Savitskaya L D 1998 Patent 2112307 RU Induction compensated electrical machinery
- [9] Mugalimov R G, Zakirova R A and Mugalimova A R 2016 *Programmny kompleks dlya rascheta i optimizatsii sebestoimosti traditsionnogo kapitalnogo remonta i remonta s povysheniem klassa energoeffektivnosti asinkhronnykh elektrodvigatelye* [A software programme for estimation and optimization of costs incurred by conventional induction motor overhaul and induction motor overhaul with efficiency upgrade]. State registration certificate no. 2016610278, registered in the Registration Book of software programmes 11.01.2016
- [10] Mugalimov R G, Zakirova R A and Mugalimova A R 2016 Energy efficient asynchronous motors, technical and economic advantages and optimization of their creation *Electrotechnical systems and complexes* no **2 (31)** pp 30–4
- [11] Mugalimov R G, Barankova I I, Zakirova R A, Mugalimova A R, Mikhailova U V and Nikiforov G V 2017 Feasibility study of the overhaul of asynchronous motors with an increase in their energy efficiency class *Bulletin of the Magnitogorsk State Technical University named after G I Nosova* no **2** pp 101–9